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LOW AC LOSS STRUCTURES IN YBCO COATED CONDUCTORS WITH FILAMENTARY CURRENT SHARING

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Low AC Loss Structures in YBCO Coated Conductors With Filamentary Current Sharing

Paul N. Barnes, George A. Levin, Chakrapani Varanasi, and Michael D. Sumption

***Abstract*—Architectural design improvements, such as filamentation, to $YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors can result in a more ac-tolerant version of the conductor. However, finely made striations in the conductor make filament breakage more probable. In this case, weakly linking the filaments can enable current sharing among the filaments of striated coated conductors while maintaining reduced hysteretic losses. Data is presented for a YBCO sample divided into superconducting filaments separated such that the transverse critical current density of the striation is significantly less than the longitudinal critical current density along the filaments. A LAO substrate was physically scribed with parallel incisions to adversely affect the subsequent epitaxial growth of the YBCO layer between the striations. Vibrating sample magnetometry measurements verified a reduction in hysteretic loss compared to a control sample of epitaxially grown YBCO on an unscribed LAO substrate. Since filamentation requires a twist in the conductor for practical applications, a discussion is also given outlining an alternate means of accomplishing this by placing a twist in the coated conductor architecture itself.**

***Index Terms*—AC losses, current sharing, hysteretic & coupling losses, YBCO coated conductor.**

I. INTRODUCTION

THE high temperature superconductor (HTS) $YBa_2Cu_3O_{7-x}$ (YBCO) is a type II high temperature superconductor capable of large current densities ($> 10^6$ A/cm^2 at 77 K, self-field), and maintains these high current densities ($\sim 10^5$ A/cm^2 at 77 K, 2 T) in applied magnetic fields. Since YBCO requires strict biaxial alignment, the most suitable form for creating an HTS conductor with YBCO is as an HTS coated conductor. The preferential characteristics of the YBCO coated conductor, especially its in-field performance, indicate potential for using this conductor in power generation applications such as superconducting generators, motors, and transformers. However, these applications can place the conductor in an environment of alternating magnetic fields.

Industry is currently focusing on development of the conductor in a dc environment, for which a YBCO thin film is deposited on a metallic substrate separated by buffer layers [1]–[4]. The result is a thin film, $\sim 0.3\ \mu$m—a few μm's thick, on a substrate with widths typically up to 1 cm, although it can be significantly wider for manufacturing. In a superconducting thin film, current flows in the outer portion of the film. This current sheath reaches the center portion of the superconductor filament when the transport current is sufficiently large in for a fully penetrated case. In the fully penetrated case, the hysteresis loss in the superconductor is proportional to the width of the thin film perpendicular to both the applied field and the current flow.

Improvements to the YBCO coated conductor can substantially reduce ac losses experience in this HTS wire. An adequately ac-tolerant version of the YBCO coated conductor can enable the all-cryogenic configuration (fully-superconducting version) for motors and generators in which both the field and armature windings are superconducting [5]. In these applications, which can include superconducting transformers as well as rotating machinery, the conductor can be exposed to high frequencies of up to a couple thousand Hz for alternating magnetic fields of up to a few Tesla. Whether an adequately ac-tolerant YBCO coated conductor can be made for the armature windings in high speed generators or not, this will be one of the most severe environments and as such represents the most aggressive goal.

There are many ac losses that can be introduced in the HTS conductor when placed in the aforementioned applications. These include hysteretic losses in the superconducting layer, coupling losses in a filamented superconducting layer, eddy current losses in both the substrate and stabilizing layer, ferromagnetic losses of the substrate, and transport current losses [6]–[8]. Although ac-tolerant substrate development often focuses on the ferromagnetic losses, greater attention needs to be placed on the induced eddy current losses.

In developing a more ac-tolerant HTS conductor, subdividing a YBCO tape into filaments can significantly decrease the hysteresis losses in ac applications [9]–[13]. Hysteresis losses in the conductor are realized as waste heat; minimizing these losses lower the refrigeration requirement The resulting multifilamentary structure is a tape with parallel thin strips of YBCO material separated by nonsuperconducting, resistive barriers. This subdivision of the HTS tape into a multifilamentary structure serves to reduce the high aspect ratio of the thin film tapes. This is necessary since the hysteresis losses of a superconducting tape are directly proportional to the width of the conductor when fully penetrated by a magnetic field. The loss per volume per cycle can be given by in SI units:

$$\frac{Q}{V} \approx \frac{1}{10} d j_c H_0 \tag{1}$$

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where d is the filament width and H_0 is the field amplitude which is large compared to the full penetration field H_p. Since filamentation of the YBCO coated conductor introduces coupling losses in ac fields [6], [14], the conductor will require twisting along its length. The twists in certain cases can be placed outside the active region of the generator or motor since twist in a flat tape will be volume inefficient.

II. Current Sharing

A. Benefit

Ii is quite possible that effective reduction of the hysteretic losses in the conductor may require the filaments of the conductor to be under 100 microns making the conductor more susceptible to minor defects in the HTS layer. Minor defects which may be ignored in unstriated wider tapes may now effectively block the current flow in a given filament. Since random and occasional defects may occur in long lengths of hundreds of meters, a substantial number of filaments may be blocked rendering the conductor useless.

One method to avoid this dilemma is to introduce current sharing in the conductor [15], [16]. If filaments can share the current flow with all remaining filaments, then the broken filament is only ineffective in the neighborhood of the defect. However, when allowing filaments to current share, it must be done in a manner that does not significantly degrade the benefit of filamentation in reducing hysteretic losses. Hysteretic losses must be kept minimal. If coupling of filaments for current sharing is induced by normal metal connections, losses will be frequency dependent. This is one of the factors that has generally precluded the consideration of superconducting wire for high frequency applications. As such, a frequency independent superconducting alternative may be a preferable solution since superconducting currents are frequency independent. Thus, it is possible to conceive of a low level superconducting connection which will enable frequency independent current sharing, while still maintaining low ac losses. This will allow the construction of highly filamented YBCO conductors with low loss, but with maximal transport properties.

A couple possibilities of introducing the current sharing can be by low critical current density (J_c) continuum-connections along the length of the filament for weak linking (as opposed to resistive barriers) displayed in Fig. 1 or by the creation of discreet microbridges for interconnectivity.

If we require that the shared critical currents over the sharing length be about that of the filamentary critical current then

$$J_{cw}L_c = J_{cf}d_f \quad or \quad J_{cw} = \frac{J_{cf}d_f}{L_c} \tag{2}$$

where J_{cf} is the filamentary J_c along strand, J_{cw} is the low-level J_c perpendicular to the filament, and d_f is the filamentary width. As an example, if $\mathrm{d_f}$ is 200 microns and the sharing length be = to a twist pitch of 20 cm, then $\mathrm{J_{cw}}$ is 1000 times smaller than $\mathrm{J_{cf}}$.

B. Low $\mathrm{J_c}$ Linkeage Example

In the case of weak linking by continuous low Jc striations, the striations can be induced in the HTS layer by affecting the substrate such that subsequent epitaxial growth of the YBCO is disrupted [15]. The use of post-processing procedures will also work. For this report, the substrate was physically scribed to adversely affect the subsequent epitaxial growth of the YBCO. YBCO growth was accomplished by pulsed laser deposition. A Lambda Physik laser, model LPX 305i, operating at 248 nm, the KrF wavelength performed the depositions. Deposition conditions are given elsewhere [15].

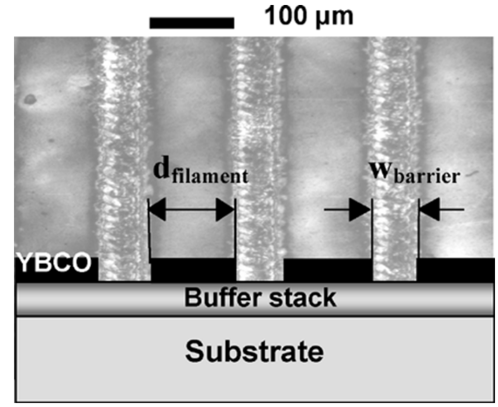

Fig. 1. A filamented YBCO sample with a cross-sectional drawing of a multifilamentary tape depicting a more ac-tolerant coated conductor.

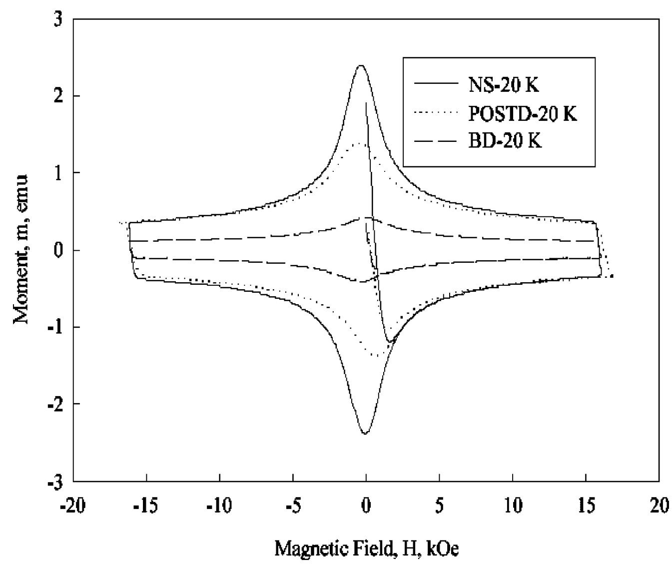

Fig. 2. The magnetization curves for the weakly linked sample and the control sample at a temperature of 20 K representing the reduction in hysteretic loss. The POSTD sample is redeposition of YBCO on scribed YBCO and regains the magnetization losses.

A dual bridge structure of a control YBCO bridge and a YBCO bridge epitaxially grown on a scribed portion was used to determine the feasibility of this process for making low $\mathrm{J_c}$ striations. Transport critical current densities across the bridges indicated an order of magnitude reduction in critical current, a low value per (2) above. For reduction of hysteretic losses, separate samples were created on LAO substrates, one substrate being scribed with six parallel striations across its length (sample BD) and the other unaffected (sample NS). YBCO was deposited on both samples with standard conditions for pulsed laser deposition. The reduction in losses is given in Figs. 2 and 3

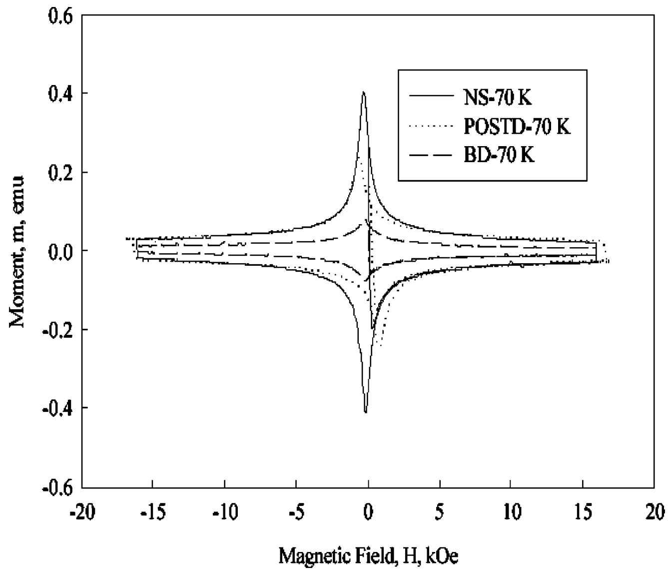

Fig. 3. The magnetization curves for the weakly linked sample and the control sample at a temperature of 70 K representing the reduction in hysteretic loss. The POSTD sample is redeposition of YBCO on scribed YBCO and regains the magnetization losses.

based on vibrating sample magnetometry measurements. The third sample (POSTD) will be referred to later.

III. Twisted Filament Conductor

An important consideration for lowering the losses in the YBCO coated conductor is that the filaments must be twisted or transposed. This can be done by bending the HTS tape itself, which although possible, does have limitations due to the bend strain tolerance of the superconductor. For bending geometry, as opposed to twisting geometry, strain will be given by

$$e \approx \frac{t_{YBCO}}{t_{cab}}$$

Where t_{YBCO} is the thickness of the YBCO in a neutral axis geometry (at best) or the distance the YBCO layer is located from center. This gives, for a 0.5% strain limitation and a $t = 25\ \mu\mathrm{m}$ a limitation on the bend radius to be no less than 1 cm with consideration for margin of error.

If a method can be devised to transpose the filaments without physically bending the superconducting material itself (as part of the HTS coated conductor), issues associated with these limitations can be largely avoided. As such, a method is considered below of transposing the filaments of a HTS coated conductor on a single tape by material processing methods. Decreased losses result in lower refrigeration loads, keeping HTS generators, motors and transformers compact. This concept of the transposed filamentary structure in an HTS coated conductor is depicted Figs. 4–6. The upper drawing in the figures provides a planar view of the concept while the lower drawing provides a side view. The drawings are simplified to show only the substrate on which the YBCO layer is deposited. Typically, there will be intervening buffer layers which are not displayed. The substrate is labeled and the black portion of the drawing is the YBCO layer.

Striations in the YBCO layer are made as depicted in Fig. 4 creating filaments in the YBCO layer at an angle to the axis of

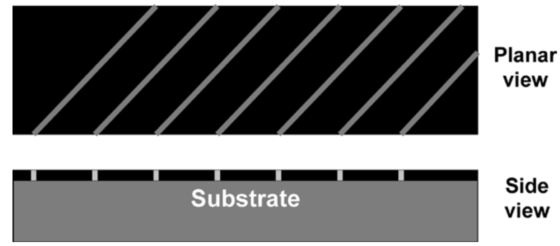

Fig. 4. A YBCO coated conductor that being prepared for transposed multifilamentary structure. Striations are made into the YBCO layer fully separating the filaments.

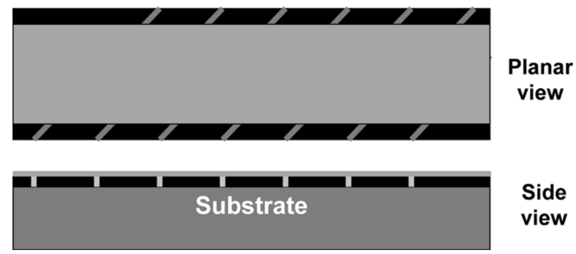

Fig. 5. A YBCO coated conductor that being prepared for transposed multifilamentary structure. An intervening insulation layer is deposited on the structure depicted in Fig. 4. This layer must provide an epitaxial template for subsequent YBCO deposition.

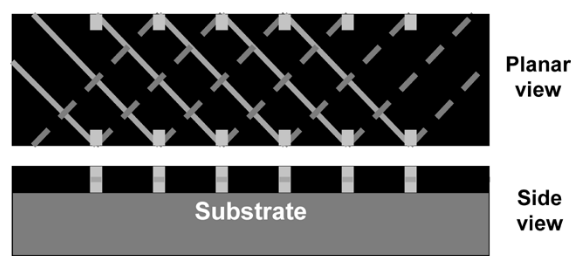

Fig. 6. A YBCO coated conductor that being prepared for transposed multifilamentary structure. A new YBCO layer is deposited on the structure given in Fig. 5 and striations are made into the new YBCO layer separating the filaments on top. The underlying filaments (separated by dashed lines) are connected to the overlying filaments at the edges of the conductor. Current flows in the c-axis direction in YBCO at the edges.

the conductor. The filaments must be fully segregated. No new material is added, the separations are made between the YBCO filaments either by a removal process, such as etching or laser ablation, or some process prior to or during deposition to affect the substrate growth such as manually scribing or cutting the filaments. On top of this filamentary structure, a new layer must now be deposited which is insulating and will electrically isolate the existing YBCO layer from a new upper layer that will be added later as in Fig. 5. This intervening layer is added such that the edges of the original YBCO layer are exposed. It will be necessary that the insulating layer also provide an epitaxial template for the subsequent YBCO layer to be deposited on top. Note that the edges of the filaments which are exposed could have been created perpendicular to the axis of the conductor as opposed to a continuation at the same angle as the filaments underneath the insulating epitaxial layer.

A new layer of YBCO must now be deposited on top of this structure as in Fig. 6. Again this layer must be striated as the first YBCO layer only the orientation of the striation represent a reflection of the original striations about an axis in the plane

of the tape, but perpendicular to the axis of the tape as represented in Fig. 6. The depth of the striations is only to the intervening insulation layer. Critical to success of the transposed structure is to maintain separation of the filaments at the edges so they are electrically isolated. Redeposition of YBCO on the previously striated bottom layer of YBCO which is exposed at the edges will result in the filaments being recoupled. Sample POSTD in Figs. 2 and 3 is a sample with YBCO redeposited on striated YBCO which effectively recoupled the filaments since the hysteretic loss is almost the same as the original value. This separation can be accomplished either after deposition of a uniform YBCO layer or maintained by physical structures when depositing the new YBCO layer. Cutting the filaments perpendicularly at the edges as mentioned previously may make this separation of filaments at the edges more readily achieved.

A continuous twisted filament is then made along the length of the coated conductor, in this case three adjacent continuously twisted filaments. Note that the filament on the top at the far right connects an underlying filament at both top and bottom of the intervening insulating layer. This structure will force currents to flow at the edges through the c-axis direction of the YBCO material. Critical currents in this direction are reduced by at least an order of magnitude or more. However, since the YBCO film is a micron or two thick, an order reduction in critical currents in the c-axis direction will force the planar width on either side of the intervening insulating layer to be 10–100 microns wide which is very reasonable for a 4 mm wide conductor. A reduction of two orders of magnitude is still just a fraction of a millimeter.

IV. Conclusion

In the coming years, hundreds of meters of high current density YBCO tape will become available for applications such as power transformers, motors, and generators. The applications will best be realized when the conductor is structured to minimize ac losses in order to keep refrigeration requirements to a minimum. As such considerations for a more ac-tolerant version of the YBCO coated conductor was discussed. In addition to filamentation, current sharing between the filaments by superconducting linkages can circumvent filament blockage while maintaining low hysteretic losses. Also a concept of transposed filaments was discussed which can avoid much of the necessary twisting when using a parallel filamentary ac-tolerant HTS conductor.

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